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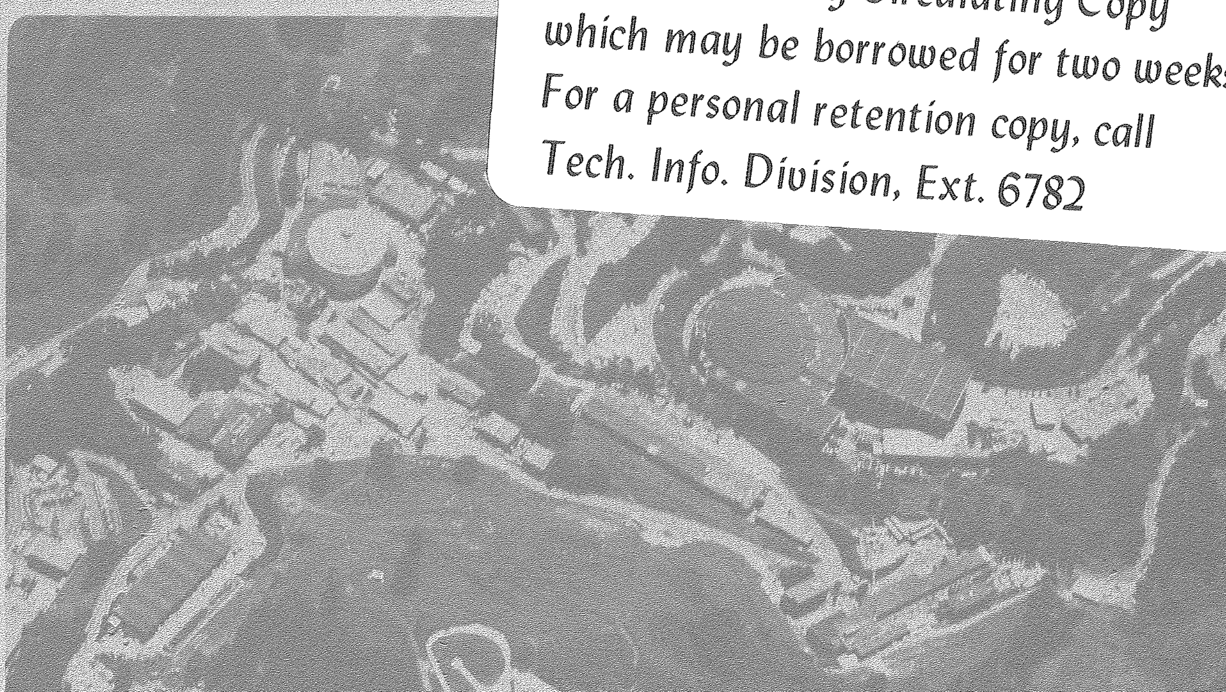



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# PRODUCTION OF CHARMONIUM STATES BY RESONANT $p\bar{p}$ ANNIHILATION*

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ABSTRACT

Cross sections are estimated for the production of charmonium states in $p\bar{p}$ annihilation on resonance. For processes like $p\bar{p} \to \eta_c \to \gamma\gamma$ the cross sections are about 1 nb. Non-resonant contributions are estimated and found to be much smaller. Similar rates are found for $p\bar{p} \to \eta_c' \to \gamma\gamma$ and $p\bar{p} \to {}^1P_1 \to \eta_c\gamma \to \gamma\gamma\gamma$. These may thus furnish a unique means of observing these charmonium states. Upsilonic states might be observable in colliding ring $p\bar{p}$ experiments, but the cross sections are likely to be in the picobarn range.

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Any resonance which can be produced in $e^+e^-$ annihilation, can, in principle be produced as well by $p\bar{p}$ annihilation. In addition, states with $J^{PC}$ differing from that of the photon, $1^{--}$, may also be produced in $p\bar{p}$ annihilation. Resonant production of the charmonium states $1^1S_0(\eta_c)$, $2^1S_0(\eta_c')$, and $1^1P_1$ would be an attractive possibility with $\bar{p}$ beams of about 4-5 GeV. Of course the coupling of these states to the $p\bar{p}$ system is likely to be feeble and the large background of purely conventional hadronic events poses a serious problem.

Here we pursue the suggestion[1] that the hadronic background can be overcome by looking for specific few body final states such as $p\bar{p} \to \eta_c \to \gamma\gamma$. It is straightforward to estimate the cross section for this and similar processes. They are in the nanobarn range, as we shall show below. The more difficult task is to estimate the non-resonant sources of the same final state. This we shall do using experimental data. Both vector meson dominance[2] and Regge treatments indicate that nonresonant cross sections are small. Our conclusion is that the non-resonant sources are probably not too serious a problem.

Certainly there are substantial difficulties besides the ones we evaluate here. The resonant cross sections are down by $10^7$ - $10^8$ from the total hadronic cross section. Most of this background can be eliminated by vetoing events with charged particles present and by excluding events where there are any particles, charged or neutral, near the forward or backward directions. The resonant processes, of course, yield events with isotropic or nearly isotropic distributions in the center of mass, unlike the typical hadronic events which peak in the forward and backward directions. The severe kinematical constraints satisfied by the events we seek could be used to reduce the background.

The cross section for production of a spin J-resonance in $p\bar{p}$ annihilation is given at the peak ( $\sqrt{s} = m_{res}$) by

$$\sigma_{res} = \frac{4\pi}{s - 4m_p^2} (2J + 1) B_i , \qquad (1)$$

where $B_i$ is the branching ratio of the resonance into $p\bar{p}$. In practice, $\bar{p}$ beams are not monoenergetic and a correction must be made for this. The spread in beam energy produces a spread in the center of mass energy, $\Delta W$. If $\Delta W$ is much bigger than the resonance width, $\Gamma_t$, the effective cross section is

$$\sigma_{eff} = \sigma_{res} \frac{\Gamma_t}{\Delta W} . \qquad (2)$$

We estimate the branching ratio of the charmonium states in $p\bar{p}$ using the data for $\psi \to p\bar{p}$. The measured branching[3] ratio is $(0.21 \pm 0.02)\%$. However, the total width for the $\psi$ includes decays through a single virtual photon which account for about 30% of the width[4]. Since these decays are absent for the particles of interest here, we use a branching ratio of about $3 \times 10^{-3}$. In this way we estimate

$$\begin{aligned} \sigma_{res}(p\bar{p} \to \eta_c) &\approx 3\mu b, \\ \sigma_{res}(p\bar{p} \to \eta_c') &\approx 1.8\mu b \qquad (3) \\ \sigma_{res}(p\bar{p} \to {}^1P_1(c\bar{c})) &\approx 5.4\mu b \end{aligned}$$



We have taken the values[5]

$$\begin{aligned} m(\eta_c) &= 2.98 \text{ GeV} , \\ m(\eta_c') &\approx 3.50 \text{ GeV} , \qquad (4) \\ m({}^1P_1) &\approx 3.50 \text{ GeV} . \end{aligned}$$

The production cross sections must now be multiplied by the branching ratios to the final states of interest. For the $\eta_c$, there are indications[6] that the total width is about 20 MeV, while the $\gamma\gamma$ decay is expected[7] to have a partial width of about 10keV. On this basis, we assume

$$\begin{aligned} B(\eta_c \to \gamma\gamma) &= 0.5 \times 10^{-3} , \\ B(\eta_c' \to \gamma\gamma) &= 0.5 \times 10^{-3} . \qquad (5) \end{aligned}$$

Combining these rates with those in Eq. (3), we have the estimates

$$\begin{aligned} \sigma_{res}(p\bar{p} \to \eta_c \to \gamma\gamma) &\approx 1.5 \text{ nb}, \\ &\qquad (6) \\ \sigma_{res}(p\bar{p} \to \eta_c' \to \gamma\gamma) &\approx 0.9 \text{ nb}. \end{aligned}$$

The competing non-resonant processes will be estimated later.

The ${}^1P_1$ resonance has the signature ${}^1P_1 \to \gamma\eta_c \to \gamma\gamma\gamma$ . The total width of ${}^1P_1$ is expected to be roughly in the same range as those of the $\psi$ and $\psi'$ since it decays through three gluons, or a little wider because of a logarithmic threshold enhancement[8].

The branching ratio, $B(^1P_1 \to \gamma\eta_c)$ can be estimated fairly reliably from a comparison with the measured branching ratio[9] $B(^3P_1 \to \psi\gamma)$ = (23.4±0.8)%. Using the theoretical relation, $\Gamma(^1P_1) = (5/6)\,\Gamma(^3P_1)$, we find

$$B(^1P_1 \to \gamma\eta_c) \approx \frac{6}{5}\, B(^3P_1 \to \gamma\psi) \left(\frac{p(\eta_c)}{p(\psi)}\right)^3 \approx 28\%. \tag{7}$$

Together with Eqs. (3) and (5), this yields

$$\sigma_{res}(^1P_1 \to \gamma\eta_c \to \gamma\gamma\gamma) \approx 0.8 \text{ nb}. \tag{8}$$

It must be borne in mind that the small total width of $^1P_1$ may result in a much smaller effective peak cross section.

If the proton were structureless, like the electron, we could calculate the non-resonant process $p\bar{p} \to \gamma\gamma$ using quantum electrodynamics. With just a Dirac coupling, the result is that the total cross section at $s = m(\eta_c)^2$ is about 30 nb. This is clearly an overestimate since we have ignored the tendency of the proton to emit additional pions when it undergoes a large momentum transfer. Indeed, it is well known that $p\bar{p}$ annihilation at $s \simeq 10$ GeV$^2$ results in final states with only two particles very infrequently.

This can be made quantitative using the vector dominance model. A bubble chamber experiment[10] with 5.7 GeV incident antiprotons found an upper limit, at 90% confidence level, of 10 μb for the reaction $p\bar{p} \to \rho^o\rho^o$. This cross section would lead to cross section for $p\bar{p} \to \gamma\gamma$ of



$$\begin{aligned}\sigma(p\bar{p} \to \gamma\gamma) &= \sigma(p\bar{p} \to \rho^o\rho^o) \cdot \alpha^2 \left(\frac{4\pi}{g_\rho^2}\right)^2 \\ &< 10\mu b \times \alpha^2 \times \frac{1}{2.3^2} = 0.1 \text{ nb}\end{aligned} \tag{9}$$

at $s \simeq 12$ GeV$^2$. Not only is this much smaller than the cross sections estimated in Eq. (6), but furthermore, the angular distribution is likely to be peaked in the forward and backward directions, unlike the distribution from the resonant process.

As a second means of estimating the non-resonant cross section, we use a very crude Regge model. The scattering $p\bar{p} \to \gamma\gamma$ is presumed to occur through N or Δ Regge exchange. This same exchange controls backward $\pi p$ scattering and backward pion-photoproduction. Using these two processes, factorization and Δ- dominance we can predict the cross section for $\gamma p \to p\gamma$:

$$\frac{d\sigma}{du}(\gamma p \to p\gamma) = 3\, \frac{\left[\frac{d\sigma}{du}(\gamma p \to p\pi^o)\right]^2}{\frac{d\sigma}{du}(\pi^- p \to p\pi^-)}\,. \tag{10}$$

The factor of three arises from the Clebsch-Gordon relation $g(\overline{\Delta^+}\pi^o p) = \sqrt{\frac{2}{3}}\, g(\overline{\Delta^{++}}\pi^+ p)$ together with a correction for the presence of two photon polarizations. The minor phase space correction has been ignored. The relation follows if the process is dominated by Δ Regge exchange. Using the data of Refs. 11 and 12, we estimate that for $P_{LAB} = 6$ GeV

$$\frac{d\sigma}{du}(\gamma p \to p\gamma) \approx 0.08 \times e^{-2.2|u|} \text{nb GeV}^{-2} \tag{11}$$

where $u$ is measured in $\mathrm{GeV}^2$. By crossing symmetry (again neglecting a small phase space correction),

$$\frac{d\sigma}{dt}\,(p\bar{p} \to \gamma\gamma) \;\approx 0.08\; e^{-2.2|t|}\,\mathrm{nb\;GeV}^{-2}. \tag{12}$$

A similar analysis can be made with $\pi^+ p \to p\pi^+$ scattering, with similar results. Integrating Eq. (12) we find

$$\sigma(p\bar{p} \to \gamma\gamma) \;\approx\; 0.04\ \mathrm{nb}. \tag{13}$$

This estimate is appropriate for $s \simeq 12\ \mathrm{GeV}^2$. To estimate the cross section at the $\eta_c$ where $s \simeq 9\ \mathrm{GeV}^2$ we must know the energy dependence of the cross section. The Regge form, $\sigma \sim s^{2\alpha-2}$, with $\alpha = 0.2$, gives a fairly small correction. In fact the data suggest a rather more dramatic $s^{-3}$ dependence. To be conservative we use this estimate. We have then

$$\sigma(p\bar{p} \to \gamma\gamma) \;\approx\; 0.1\ \mathrm{nb} \tag{14}$$

at $s = 9\ \mathrm{GeV}^2$. This crude estimate is in reasonable agreement with the vector dominance estimate. Although neither ought to be trusted to more than a factor of two, they are reassuringly small, especially since most of the cross section will be peaked in the forward and backward directions.

The background for $\bar{p}p \to {}^1P_1 \to \gamma\gamma\gamma$ comes from several sources. The purely electromagnetic process analogous to $e^+e^- \to \gamma\gamma\gamma$ would yield about 0.2 nb if the proton form factors were ignored. In



fact, the form factors will suppress the cross section considerably. A second source of $\gamma\gamma\gamma$ final states is the two-body process $p\bar{p} \to \gamma\pi^0$, and its analogues, $p\bar{p} \to \gamma\eta$ and $p\bar{p} \to \gamma\eta'$. These cross sections can also be estimated using Regge analysis. Again we use the measured cross section[11] for $\gamma p \to p\pi^0$. Using crossing and adding together the forward and backward $\pi^0$ production we have

$$\frac{d\sigma}{dt}(p\bar{p} \to \pi^0\gamma) + \frac{d\sigma}{dt}(p\bar{p} \to \gamma\pi^0) \;=\; 2\,\frac{d\sigma}{du}(\gamma p \to p\pi^0)$$

$$\approx 15 \times e^{-2.8|t|}\,\mathrm{nb\;GeV}^{-2}$$

at $p_{LAB} = 6$ GeV, and

$$\sigma(p\bar{p} \to \pi^0\gamma) \approx \;5\ \mathrm{nb}, \quad \text{at } \sqrt{s} = 3.5\ \mathrm{GeV}. \tag{14}$$

This is consistent with $\sigma(p\bar{p} \to \pi^0\gamma) < 80$ nb at $p_{LAB} = 6$ GeV, the limit obtained using vector dominance and the existing experimental upper limit[13] on $\sigma(p\bar{p} \to \pi^0\rho^0)$. The $\eta$ and $\eta'$ have weaker couplings to $p\bar{p}$ and we estimate[14] at $\sqrt{s} = 3.5$ GeV

$$\begin{aligned} \sigma_{tot}(p\bar{p} \to \eta\gamma) \times B(\eta \to \gamma\gamma) &\approx 0.07\ \mathrm{nb},\\ \sigma_{tot}(p\bar{p} \to \eta'\gamma) \times B(\eta' \to \gamma\gamma) &\approx 0.05\ \mathrm{nb}. \end{aligned} \tag{15}$$

These events would have to be separated from the true ${}^1P_1 \to \gamma\eta_c \to \gamma\gamma\gamma$ signal by kinematic constraints. Once again, eliminating events with forward and backward production would suppress the background considerably.

An alternative to searching for neutral final states is to use the clear leptonic signature of $\psi$ decay. For example, using Eq. (1) and the known leptonic branching ratios, we have

$$\sigma(p\bar{p} \to \psi \to \mu^+\mu^-) \approx 0.36\mu b,$$

$$\sigma(p\bar{p} \to \psi' \to \mu^+\mu^-) \approx 0.03\mu b. \tag{16}$$

The competing backgrounds are negligible. It should be possible, as well, to observe $\bar{p}p \to \chi \to \gamma\psi \to \gamma\,\mu^+\mu^-$. Estimated cross sections are given in Table I.

We conclude with some speculations on the possibility of observing upsilonic states using $p\bar{p}$ colliding rings. The branching ratios of the resonances into $p\bar{p}$ might well be lower by a factor of ten than those assumed for the charmonium states. In addition, the unitarity limit, Eq. (1), is lower by a factor of ten as well. Even if the branching ratio were $0.5 \times 10^{-3}$, the cross sections of interest would be about $10^{-35}$ cm$^2$. While this would give a few events per hour given a luminosity of $10^{32}$ cm$^{-2}$sec$^{-1}$, it is not clear that this is really practicable. It may be feasible to explore the $^3P_1$ and $^3P_2$ states of $(b\bar{b})$ through $\gamma\ell\bar{\ell}$ final states, since the analogous $(c\bar{c})$ states are predicted to have relatively large production cross sections.

In summary, we find that the resonant production cross sections for charmonium states in $p\bar{p}$ annihilation are large enough (in the nanobarn range) to permit observation, even for some states which have not been seen in $e^+e^-$ annihilation. The non-resonant cross sections which compete are estimated to be smaller than the resonant cross sections. Estimates for the production of $(b\bar{b})$ states are less certain, but the cross-sections are considerably smaller, perhaps in the picobarn range. Even in the charmonium



case, extremely careful experiments will be required to find the events of interest which are only a few parts in $10^8$ of the total cross section.

We would like to thank our colleagues M. Alston-Garnjost, R.W. Kenny, and T.P. Pun for bringing this problem to our attention and for their explanations of the attendant experimental problems. In addition, we would like to thank J. D. Jackson, H. Steiner, and F. Gilman for their suggestions.

TABLE I

Estimated peak resonant production cross sections for formation of charmonium states in $p\bar{p}$ annihilation. The background processes are non-resonant cross sections with the same final state as the resonant process. A dash in the final column indicates that the cross section is negligible.

| Signature | Resonant Cross Section (nb) | Non-resonant process | Non-resonant Cross Section (nb) |
|---|---|---|---|
| $p\bar{p} \to \eta_c \to \gamma\gamma$ | 1.5 | $p\bar{p} \to \gamma\gamma$ | 0.1 |
| $p\bar{p} \to \eta_c' \to \gamma\gamma$ | 0.9 | $p\bar{p} \to \gamma\gamma$ | 0.04 |
| $p\bar{p} \to {}^1P_1 \to \gamma\eta_c \to \gamma\gamma\gamma$ | 0.8 | $p\bar{p} \to \gamma\pi^0 \to \gamma\gamma\gamma$ | 5 |
| | | $\to \gamma\eta \to \gamma\gamma\gamma$ | 0.07 |
| | | $\to \gamma\eta' \to \gamma\gamma\gamma$ | 0.05 |
| $p\bar{p} \to \psi \to \mu^+\mu^-$ | 400 | $p\bar{p} \to \mu^+\mu^-$ | - |
| $p\bar{p} \to \psi' \to \mu^+\mu^-$ | 30 | $p\bar{p} \to \mu^+\mu^-$ | - |
| $p\bar{p} \to \chi_0 \to \gamma\psi \to \gamma\mu^+\mu^-$ | 5 | $p\bar{p} \to \gamma\psi \to \gamma\mu^+\mu^-$ | - |
| $p\bar{p} \to \chi_1 \to \gamma\psi \to \gamma\mu^+\mu^-$ | 90 | $p\bar{p} \to \gamma\psi \to \gamma\mu^+\mu^-$ | - |
| $p\bar{p} \to \chi_2 \to \gamma\psi \to \gamma\mu^+\mu^-$ | 100 | $p\bar{p} \to \gamma\psi \to \gamma\mu^+\mu^-$ | - |



REFERENCES


1. T. P. Pun, private communication.
2. We thank J. D. Jackson for reminding us of this tried and true procedure.
3. Particle Data Group, Review of Particle Properties, Phys. Lett. 75B (1978) 1.
4. Cited in particle Data Group compilation, Ref. 3. Included are the decays into $e^+e^-$, $\mu^+\mu^-$, and an additional amount equal to about twice the partical width into $e^+e^-$, corresponding to second order electromagnetic decays into hadrons.
5. The $\eta_c$ mass is that found by the Crystal Ball Experiment, E. Bloom, Invited talk at 9th International Symposium on Lepton and Photon Interactions at High Energy, Batavia, IL, August 23-29, 1979.
6. A preliminary result of the Crystal Ball Group, given by T. Burnett at the Irvine Conference, November 30, 1979.
7. T. Appelquist and H. D. Politzer, Phys. Rev. D12, (1975) 1404.
8. R. Barbieri, R. Gratto, and E. Remiddi, Phys. Lett. 61B, (1976) 465.
9. Cited in Particle Data Group compilation, Ref. 3.
10. A. Accensi, et al., Physics Letters 20, (1966) 557.
11. D. Tompkins et al., Phys. Rev. Lett. 23 (1969) 725. V. Barger and P. Weiler, Phys. Letters 30B, (1969) 105.
12. A. Ashmore et al., Phys. Rev. Lett. 19, (1967) 460 and Phys. Rev. Lett. 21, (1968) 387; J. Orear et al., Phys. Rev. Lett. 21, (1968) 389; V. Barger and D. Cline, Phys. Rev. Lett. 21, (1968) 392.

13. T. Ferbel et al., Phys. Rev. 173, (1968) 1307.

14. Only $N$ exchange contributes to the processes. SU(3) symmetry gives the relation between the Regge residues,

$$\beta^2(\bar{p}p\eta) = \frac{1}{3}\left(\frac{D-3F}{D+F}\right)^2 \beta^2(\bar{p}p\pi^0),$$

where the $D$ and $F$ are the usual octet pseudoscalar meson baryon couplings.